Stability of Clay-Rich Fault Gouge at Intermediate to High Shear Strain

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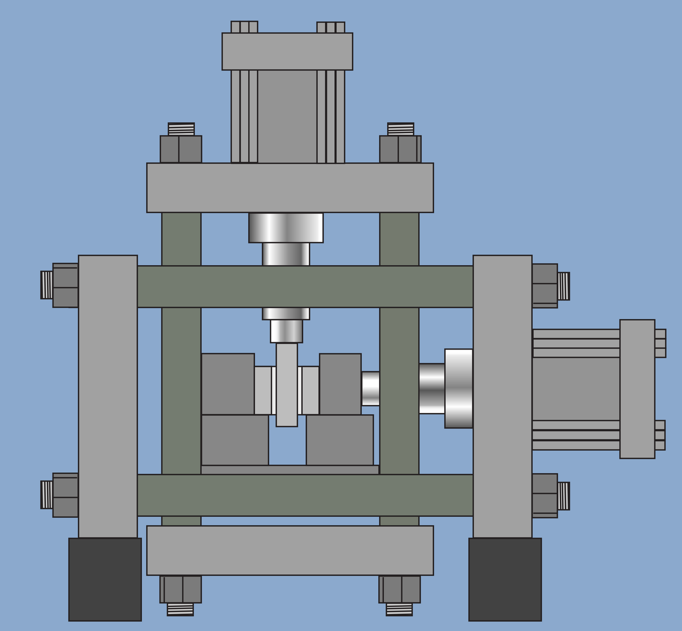
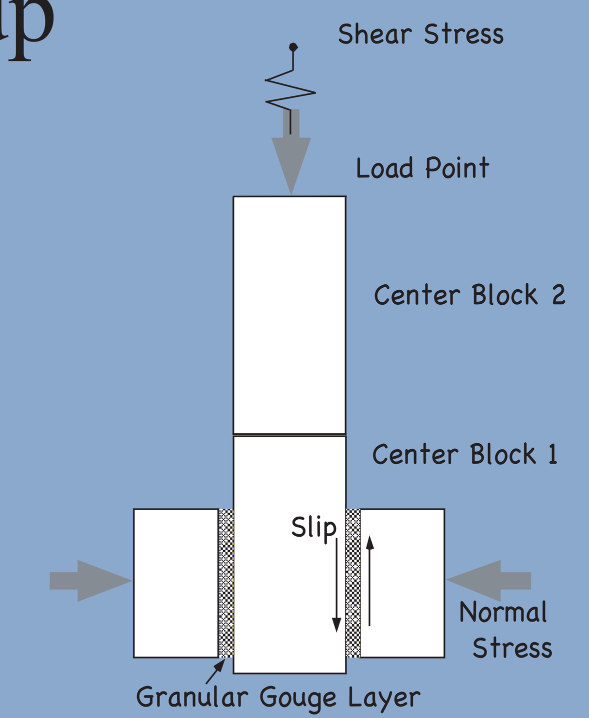
Abstract

Understanding the frictional properties of fault gouge is crucial to understanding the generation and nature of earthquakes. Clay minerals are a major constituent of fault gouge and are of particular interest because they may exhibit exceptionally low friction. Previous work has demonstrated that at shear strains up to ~15, clay-rich gouges are velocity strengthening (stably sliding) over a wide range of normal stresses and sliding velocities. However, it has been hypothesized that shear localization at high strains may cause a transition from stable to unstable frictional behavior in such gouges. Here, we report on laboratory experiments that investigate in detail the relationship between shear strain and sliding stability for a suite of clay-rich gouges. We studied six fault gouge compositions: naturally occurring chlorite schist and illite shale, commercially obtained montmorillonite, kaolinite and sand-sized quartz, and a 50%-50% mixture of montmorillonite and silt-sized quartz. We conducted experiments in a servo-controlled apparatus using the double-direct shear configuration under constant shear velocity boundary conditions. To achieve intermediate to high shear strain, we employed a new technique in which shear displacement is unlimited via use of a replaceable centerblock. Layers were initially 3 to 5 mm thick with nominal contact dimensions of 5 cm by 5 cm. For each gouge mixture we measured frictional properties at normal stresses of 15, 50, and 100 MPa and conducted velocity stepping experiments in the range 1-300 mm/s at strain intervals of ~10-20. We report values of (a-b) as a measure of gouge stability; a positive value of (a-b) indicates velocity-strengthening behavior associated with stable sliding, whereas negative values indicate velocity-weakening behavior associated with instability and potentially seismic slip.

Experimental Setup

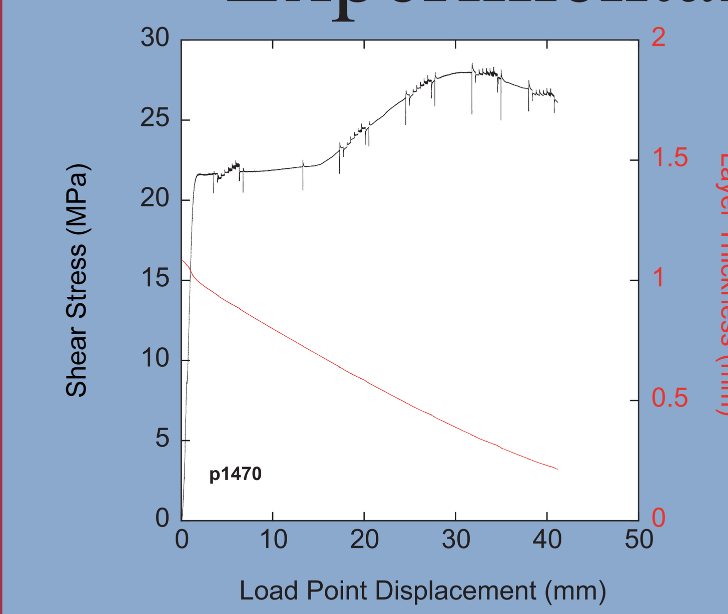


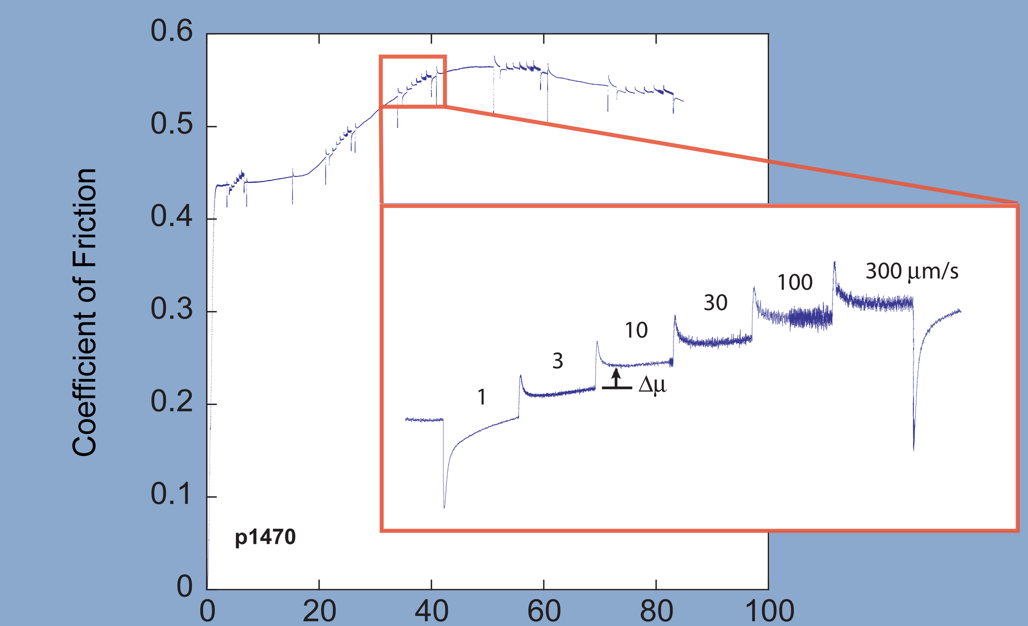


- Servo-controlled biaxial testing apparatus
- Horizontal ram applies normal load
- Vertical ram induces shear

- Double-direct shear configuration
- Contact area: 5 cm x 5 cm
- Grooved contact area to ensure slip within layer and not at contact boundary
- Two center blocks allow infinite displacement

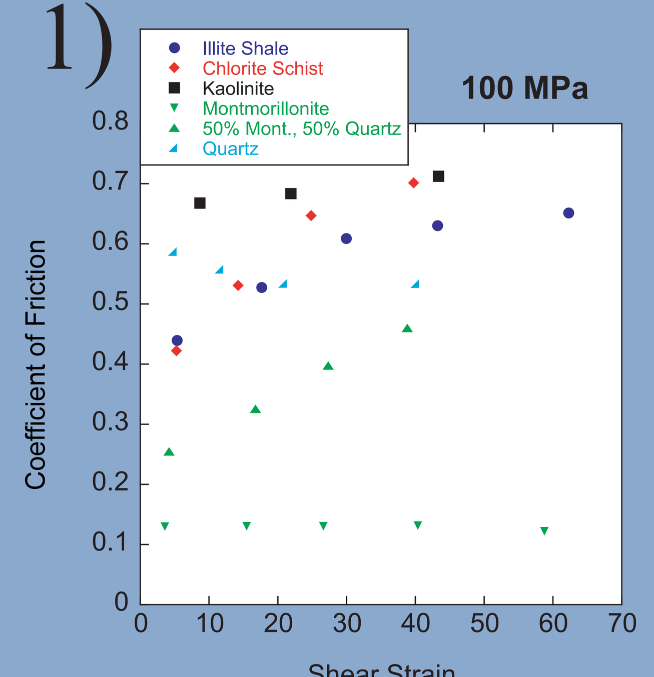
Experimental Procedure





- One normal stress in each experiment
- Velocity stepping sequence: sliding velocity is increased from 1-3, 3-10, 10-30, 30-100, and 100-300 µm/s and then back to a background velocity of 10 µm/s
- Velocity stepping sequences run at strain intervals of 10-20
- Coefficient of friction values taken before each velocity step sequence
- Shear strain calculated as $\gamma_n = \sum_{i=m}^{n} \frac{x_m - x_{m+1}}{h_{m+1}} + \dots + \frac{x_n - x_{n-1}}{h_n}$ (x=displacement, h=layer thickness)
- Friction rate dependence (a-b) values are computed as: $(a\text{-}b) = \Delta\mu/\ln(v/v_o)$

1)



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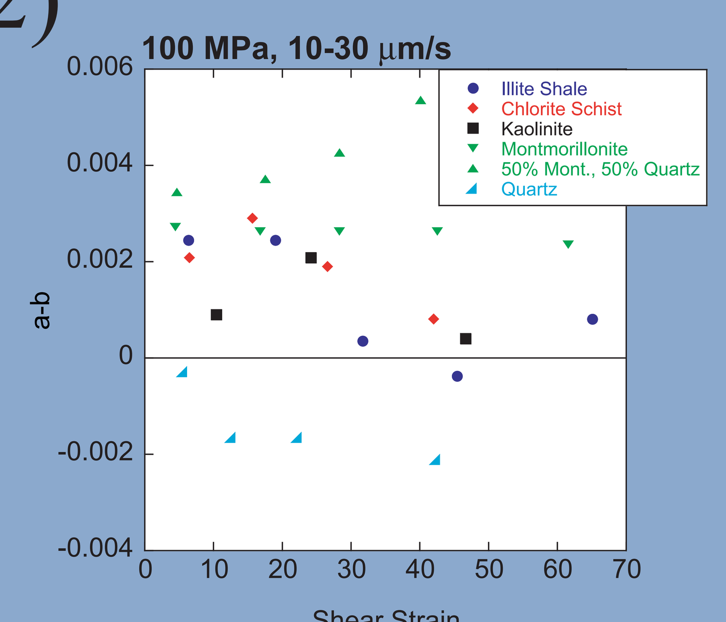

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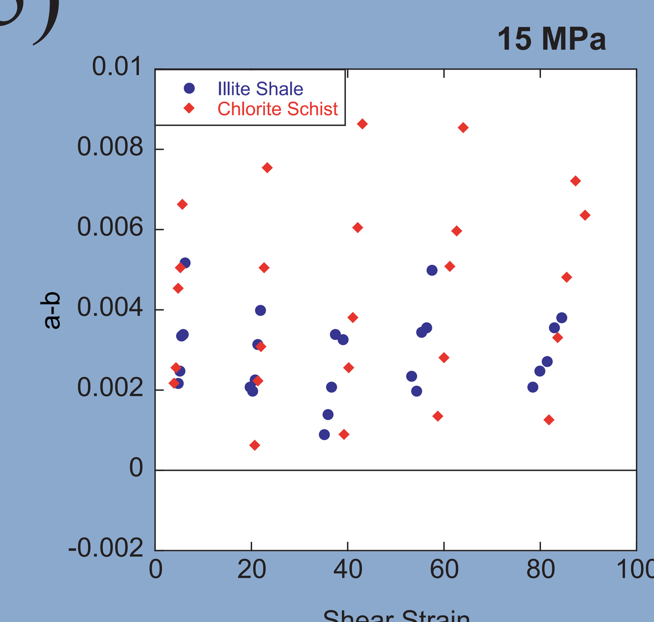

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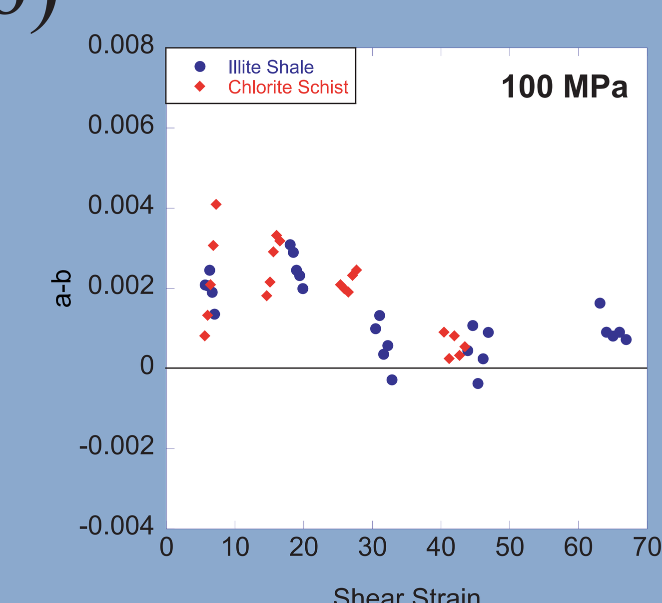

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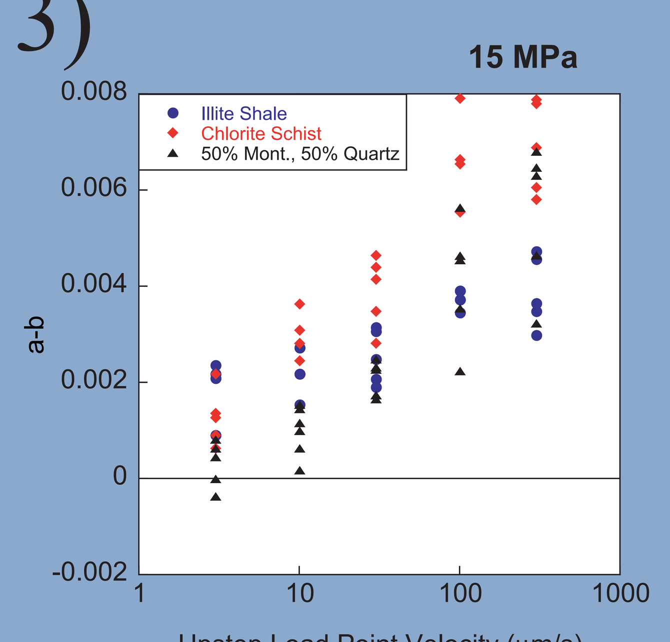

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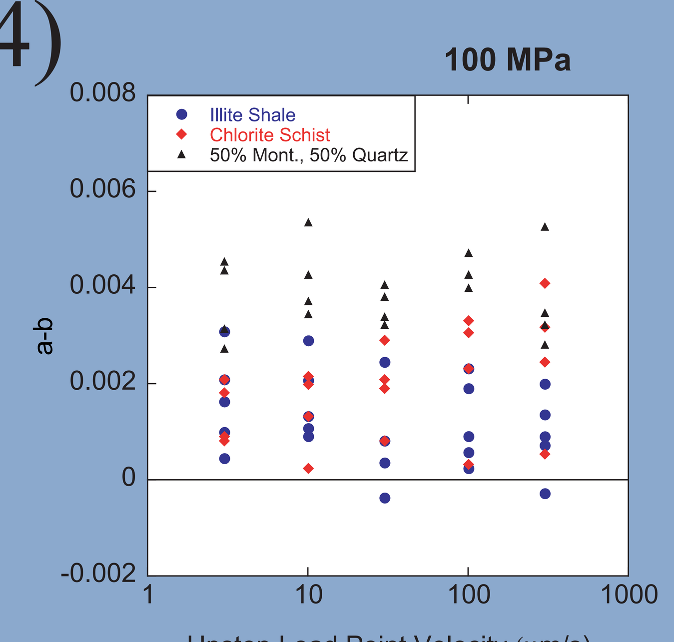

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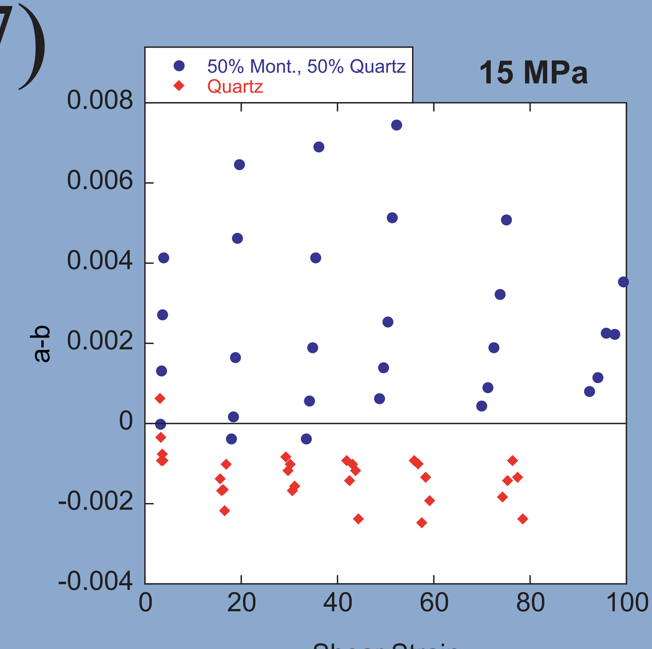

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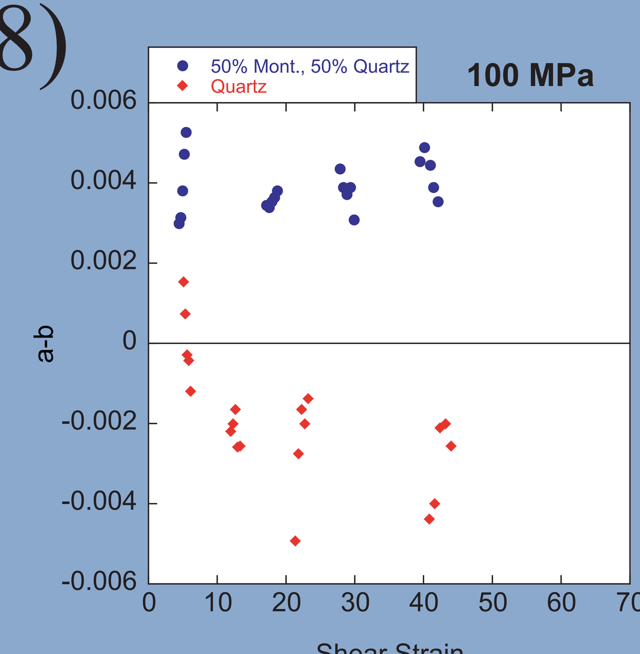

1) Coefficient of friction vs. shear strain for all gouge materials at 100 MPa normal stress. Coefficient of friction values are taken at a background velocity of 10 µm/s. Most materials exhibit strain-hardening behavior.
2) (a-b) vs. shear strain for all gouge materials at 100 MPa normal stress, for a velocity jump from 10-30 µm/s. While most materials are velocity-strengthening, there is significant variation in the degree of dependence of (a-b) on strain.
3) (a-b) vs. upstep load point velocity at 15 MPa normal stress for illite shale, chlorite schist, and 50% montmorillonite-50% Minusil 40 (silt-sized) quartz at all strains. (a-b) increases with increasing velocity.
4) (a-b) vs. upstep load point velocity at 100 MPa normal stress for the same gouge materials as in Figure 4 at all strains. Gouges are still mostly velocity-strengthening, but (a-b) no longer shows a positive dependence on velocity.
5) (a-b) vs. shear strain for illite shale and chlorite schist at 15 MPa normal stress, at all velocities. These gouges are all velocity-strengthening and show no dependence on shear strain.
6) (a-b) vs. shear strain for illite shale and chlorite schist at 100 MPa normal stress, at all velocities. Gouges tend to become less velocity-strengthening with increasing shear strain.
7) (a-b) vs. shear strain for 50% montmorillonite-50% silt-sized quartz and F110 (sand-sized) quartz at 15 MPa normal stress for all velocities. The montmorillonite gouge is mostly velocity-strengthening while the quartz gouge is mostly velocity weakening. Neither has a strong dependence on shear strain.
8) (a-b) vs. shear strain for 50% montmorillonite-50% silt-sized quartz and F110 (sand-sized) quartz at 15 MPa normal stress for all velocities. The montmorillonite gouge is again velocity-strengthening and the quartz is again velocity-weakening with no strong dependence on shear strain.

Conclusions

- Clay-rich fault gouge exhibits mostly velocity-strengthening behavior; quartz gouge is mostly velocity-weakening.
- At low normal stress, (a-b) increases with increasing velocity. At high normal stress, (a-b) is independent of velocity.
- At low normal stress, chlorite and illite gouges are velocity-strengthening with no dependence on strain. At high normal stress, increasing shear strain tends to make the gouge less velocity-strengthening.
- For most gouge materials, shear strain does not have a strong influence on fault gouge stability; factors such as normal stress, sliding velocity, and gouge mineralogy may be more important.
- In natural faults, high shear strain may make a limited contribution to the onset of seismic slip in chlorite- and illite-rich gouge.